

## Formability created by the Bauschinger effect?

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This paper describes tests to determine if the Bauschinger effect can act as an additional source of formability, this may possibly explain the enhanced formability observed in incremental sheet forming. Small cylindrical products have been made by deep drawing and wall ironing. The upper edges have been necked to various levels of reduction. Tensile test specimens have been cut from the necked upper edges and tested, causing an almost perfect stress/strain reversal. An increase of strain could be observed indeed. The results are discussed using the Considère condition as a guideline.

### Introduction



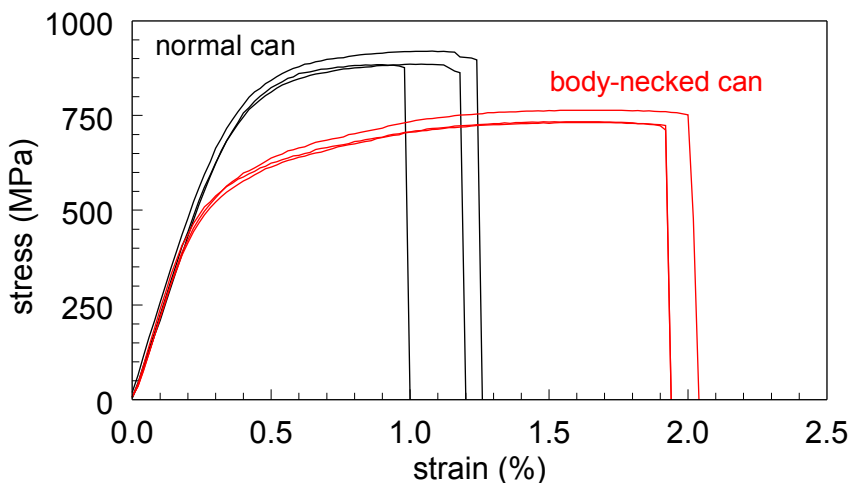
**Figure 1.** A two-piece can in early production stage, the diameter has been reduced from 66 mm to 62 mm over a large part of the height (body-necked).

In cases of classic stamping the formability of the material is restricted by the occurrence of instabilities that cause fracture. These limits are expressed by the well known Forming Limit Curve (FLC). However situations have been encountered as well where the material could be stretched well above the FLC without fracture. This is for example the case in Incremental Sheet Forming (ISF). A special variant of ISF is the shaping of beer and beverage cans by means of a high pressure water jet, this has been described before in detail [1,2].

So far little effort seems to be made to find out why in ISF the material shows enhanced formability. One of the possible mechanisms that has been mentioned is the Bauschinger effect. This paper describes tests that have been carried out to check if this claim is true. As this was done with a background in can shaping, can making techniques and equipment present at Corus have been used throughout.

The purpose of can shaping is to give the can a more fanciful shape so that the consumer can distinguish the brand easily in the supermarket. Normally this is achieved by changing the overall contour of the can, and this is done by moving some parts of the wall outwards. A consequence is that the outside dimensions increase but this is limited: a too large increase will make it impossible to handle the can in standard production lines. A possible solution put forward is to initially decrease the can dimensions as shown in figure 1 (this process is called body-necking). In this way a change of overall contour can be achieved without expanding the can too much.

Expanding the can after necking causes a stress/strain reversal, and this might evoke the well-known Bauschinger effect. It had been suggested that this effect would also increase the formability of the heavily cold worked can wall but no evidence could be found that supported this. Therefore a preliminary test was carried out by taking some tensile test samples out of the wall of a body-necked can and comparing those to samples taken from comparable unnecked cans, the result is shown in figure 2. There is indeed an increase of formability expressed by the fracture strain, this increase may look very small but it is still relevant. This result was sufficient to start a more systematic approach.



**Figure 2.** Tensile test results (engineering) taken from a body-necked can as in figure 1, and from a comparable standard can; tested in tangential direction.

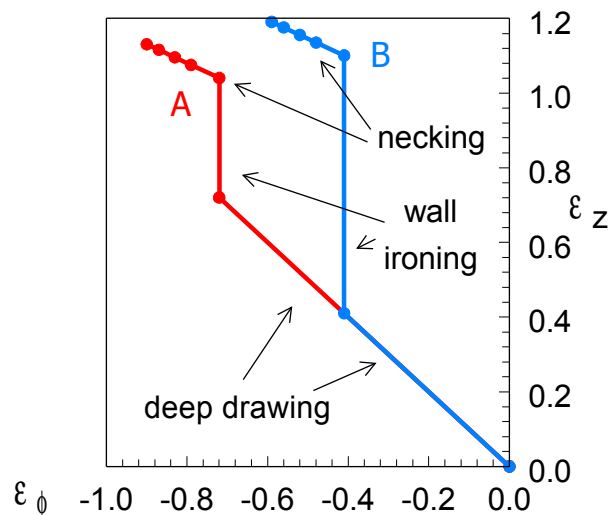
## Experimental procedures

Blanks of 136 mm diameter were cut from standard 0.22 mm thick can stock material. The blanks were deep drawn into 66 mm diameter cups. One half of the cups were wall ironed to 160  $\mu\text{m}$  wall thickness (series A), the other half to 110  $\mu\text{m}$  wall thickness (series B). All cups were trimmed to 75 mm height. The cups were subsequently

necked to different levels of reduction (meaning decrease of diameter) using a standard die-necker. This is always done in small steps to limit the axial load on the cups, and to limit the possibility of wrinkling. From the total collection of cups series were collected with approximately 7%, 12%, 16% and 20% necking reduction; samples are shown in figure 3. The total forming history (calculated) of the upper edge of the cups is presented in figure 4.



**Figure 3.** Products used for the tests made by deep drawing, wall ironing and necking; the diameter is 66 mm. Tensile test specimens were cut from the upper, necked part in tangential direction.



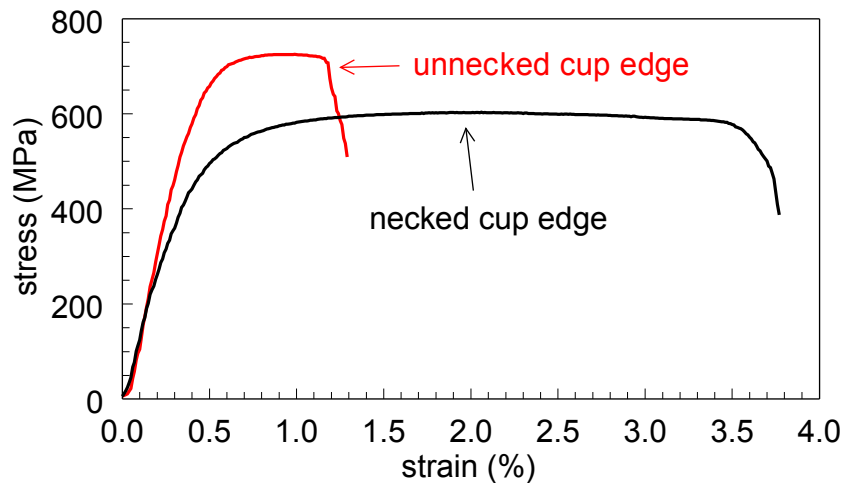
**Figure 4.** Overview of the forming history (calculated) of the upper edge of the products used in the tests. Series A had a final wall thickness of 160  $\mu\text{m}$ , series B of 110  $\mu\text{m}$ . The difference in deep drawing deformation is caused by the fact that for series B a relatively large part of the wall had to be removed to obtain a cup height of 75 mm.

Following tensile test samples were cut from the upper part of the cups in tangential direction and tested. Note that necking with a die (contrary to necking with rolls) creates an almost perfect uniaxial compressive state in the wall. This means that when performing the tensile tests, that also creates a uniaxial state, the stress/strain state is almost perfectly reversed. Due to the relatively large cup diameter (compared to the wall thickness) the strain state is more or less uniform over the material thickness. This presents an ideal situation to study the Bauschinger effect.

## Results

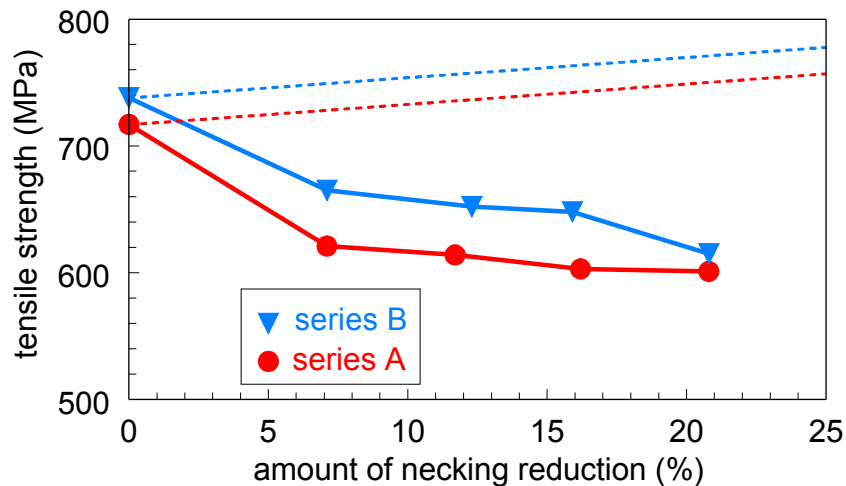
Tensile specimens were cut from the upper (necked) part of all cups in tangential direction and tested. All tests were performed threefold, the data presented following presents the mean of these three measurements. Figure 5 presents two stress-strain curves (engineering) that are typical. The curve for the unnecked situation is typical for heavily cold worked material like that of the can wall; the amount of hardening is well beyond the stability limit and the material fractures immediately (some plastic deformation still occurs due to the high level of strain-rate hardening of steel). From all curves the following data were obtained:

- the tensile strength (UTS)
- the uniform elongation
- the total elongation at fracture



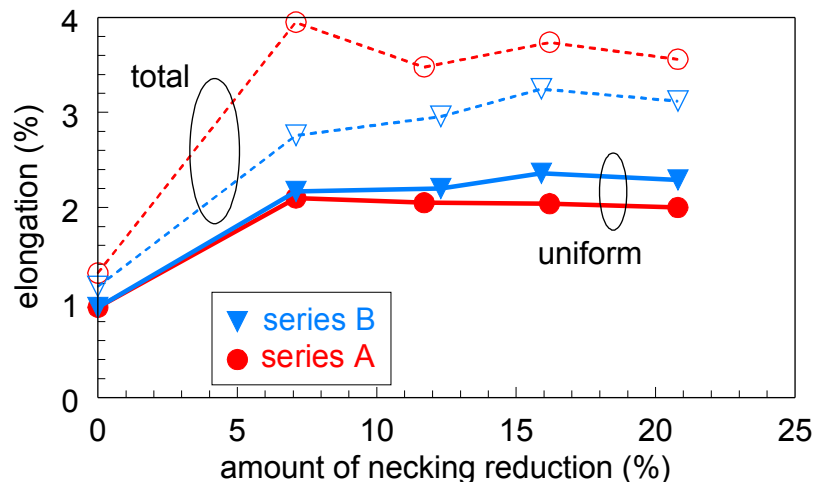
**Figure 5.** Two typical stress-strain curves (engineering) taken from the upper part of the products.

Ideally the yield stress of the material should be examined to study the Bauschinger effect. However this is difficult to determine from the tensile curves (see figure 5). So the tensile strength has been used instead, this differs only slightly from the yield stress due to the low amount of plastic straining; the results are presented in figure 6. If there would not be a Bauschinger effect we would expect the strength to increase with increasing necking reduction as the material has been subjected to additional deformation, this is shown with the dotted lines (the slope is based on general assumptions). However we see that the strength decreases instead, and also that the decrease of strength is larger for larger necking reductions with little difference between the series A and B. This observation that the strength decreases with increasing reduction is remarkable; it is not known if this is a common result of the Bauschinger effect. It may also be caused by the fact that the necking operation itself causes a change in strain path (see figure 4) and the observed behaviour may still be a remnant of that.



**Figure 6.** Reduction of tensile strength as observed from the tensile tests. The dashed lines indicate the expected strength without the Bauschinger effect.

The measured elongations are presented in figure 7. We clearly see an increase of elongation due to the necking process. Note that this increase is basically independent of the necking reduction. The uniform elongation shows little difference between series A and B, only in the total elongation we see a difference the cause of which is unknown (and not investigated). The increase in formability (strain) seems to be an on-off case: the effect is simply there or it is not, independent of the forming history.



**Figure 7.** Increase of formability expressed as elongation (uniform and total) measured from the tensile tests.

## Discussion

To understand these phenomena we have to look more specifically to what the Bauschinger effect in fact is. Figure 8 shows a recorded stress-strain curve for high strength steel that clearly shows the effect. The Bauschinger effect is best known for its reduction of the momentary yield stress, that effect can be seen at B in figure 8 ("Permanent stress offset"). However we are more interested in another effect also shown in figure 8: the stress-strain curve for the reversed state (below the zero line)

does not show a distinct yield point as the original curve, but a more gradual transition from situation A to situation B, this is indicated as the “Transient Bauschinger effect”. This can also be seen in figure 9 that presents stress-strain curves for pre-strained material with varying changes in strain path. For abrupt changes an overshoot is seen, but for more gradual changes in strain path a transient effect is clearly visible as well. This transient effect can also be noticed in the two curves in figure 5: for stresses above 200 MPa the curve for the necked cup already deviates from the elastic line.

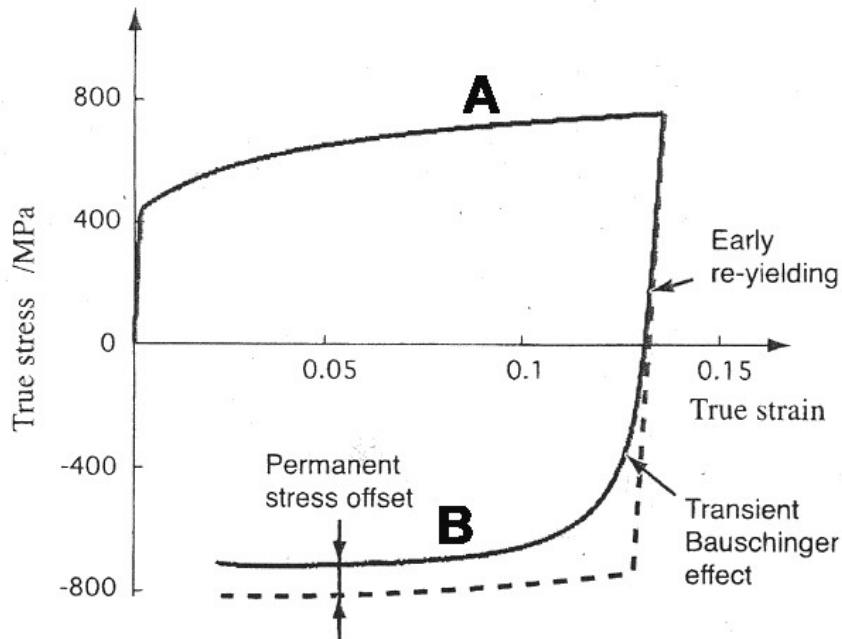


Figure 8. Typical phenomena during stress reversal: the Bauschinger effect [3].

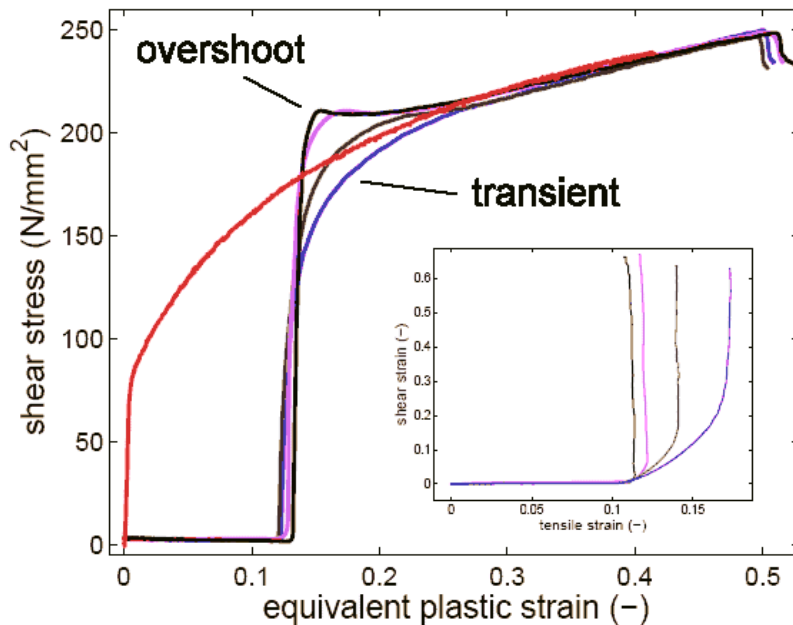


Figure 9. Stress-strain curves for pre-stressed material showing typical effects [4].

In stretching operations (including the tensile test) formability is limited by the occurrence of instabilities. The so-called Considère condition tells that the tensile test operation is stable as long as:

$$\frac{d\sigma}{d\varepsilon} > \sigma \quad (1)$$

where  $\sigma$  and  $\varepsilon$  are the true stress and true strain respectively. This applies to ANY situation where the stress is increasing with strain, regardless of the underlying metallurgical processes. We can now understand what is happening: the transient effect creates a situation where there is again considerable 'hardening' meaning that  $d\sigma/d\varepsilon$  is large again over a certain range of strain.

In figure 8 the range in strain of the transient effect is approx. 4%, in figure 9 it is approx. 15%. It is not known if these values are typical and comparable to our situation. The observed effect in our tests is much smaller and this may be disappointing to the reader: the uniform elongation increased only from 1% to 2% (figure 7). Although this is a doubling, the absolute size is very small. However this is not unexpectedly. The can wall material is very hard ( $\sigma = 700-800$  MPa) and the rate of hardening has dropped to low levels ( $d\sigma/d\varepsilon = 150-200$  MPa). Comparing this to equation (1) makes it clear that it will be very difficult to change the situation in such a way that the condition is met again. It can hardly be expected that the Bauschinger effect will decrease  $\sigma$  sufficiently to satisfy (1), so we can only expect the transient effect to be effective if at all. Nevertheless an increase of strain is observed, even in these awkward situations. The results of figure 7 suggest that the effect is independent of the forming history, but for the moment this is just speculation.

However in softer materials the situation will be different. If a material is stretched somewhat beyond the stability limit (by some means) we have a situation that  $d\sigma/d\varepsilon$  is not too much smaller than  $\sigma$ . The Bauschinger effect will both increase  $d\sigma/d\varepsilon$  (maybe considerably, transient effect) and decrease  $\sigma$  (permanent effect) meaning that the situation becomes stable again. If the material is hardened somewhat more the permanent effect may not be sufficient to lower  $\sigma$  sufficiently any more, but the transient effect is always there. As only a (relatively) small increase of  $d\sigma/d\varepsilon$  is sufficient, the effect is expected to be larger than found in the tests. This implies that for soft material the increase of formability by the Bauschinger effect is expected to be (much) larger than observed in the tests presented here.

Nevertheless, we observe that the formability of the can walls does increase and this simply proves that the proposed mechanism does exist.

## Conclusions

- Transient effects like the transient Bauschinger effect can create enhanced formability in materials subjected to changes in strain path in general, and to cyclic bending/unbending operations specifically.
- Necking of cylindrical parts allows compression in uniaxial mode, this is ideal for studying the Bauschinger effect. Material to be studied in the undeformed state

can be tested by necking cylinders manufactured by bending and welding as in common 3-piece food cans.

## References

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